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Pinning fields in amorphous materials

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The stress and field dependence of the pinning field H_p of ribbons of the composition $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ and $Co_{73.5}Cu_1Nb_3Si_{13.5}B_9$ is compared with that of the coercivity H_C. The similar character of $H_C(\sigma)$ and $H_p(\sigma)$ indicates a strong correlation between these two properties. At higher external stresses $H_C(\sigma)$ and $H_p(\sigma)$ depend on a premagnetizing procedure. This can be explained assuming a different domain structure.

I. INTRODUCTION

Amorphous ferromagnetic alloys behave magnetically soft because the domain walls are, due to their low anisotropy, broad. Additionally, the generally important pinning centers such as dislocations and grain boundaries are nonexistent. Various experimental studies of the coercivity, the initial susceptibility, and also disaccommodation experiments showed that the interaction between frozen in stresses and the magnetostriction determines the magnetization process.[1-3] Therefore, the motion of the domain walls under low external fields can be used to obtain information about the responsible mechanism in amorphous materials. Measuring the initial susceptibility by applying an ac field with increasing amplitude is a simple, powerful method for studying the domain-wall movement.[4] In the present investigation the stress dependence of the initial susceptibility is used to study the domain movement in amorphous materials. Additionally, the coercivity is measured in order to see correlations between these two properties.

II. EXPERIMENT

Two $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ ribbons with different quenching rates and a positive magnetostriction, produced in different laboratories, were compared. Sample A (thickness 25 μm) was produced by Vacuumschmelze GmbH, Hanau, Germany; whereas sample B (thickness 40 μm) was produced at Istituto Elettrotecnico Nazionale "Galileo Ferraris," Torino, Italy. Additionally, a ribbon of composition $Co_{73.5}Cu_1Nb_3Si_{13.5}B_9$—sample C—(negative magnetostriction) was produced by us using a single roller technique. All samples were measured at room temperature in the as-cast state.

The field and stress dependence of the magnetization (hysteresis loop, coercivity) was measured using a quasistatic fluxmeter method, which means that a full loop is achieved between 60 and 180 s. The absolute accuracy of the induction values is ±2%. The pinning field is measured in the same experimental setup as the hysteresis loop. The length of the magnetization pickup coil is 40 mm, which determines the averaging volume. The pinning field was measured using a lock-in technique. The ac field was applied at a frequency of 430 Hz. A premagnetizing dc field can be applied by a Helmholtz pair causing a field parallel to the ribbon axis. In order to create a well-defined domain structure, the ribbons were field demagnetized starting from the maximum field of the previous experiment and decreasing H_{ext} systematically. Investigations have shown that the experiments are otherwise not reproducible.

III. RESULTS AND DISCUSSION

Figure 1 shows the susceptibility χ of sample A as a function of the ac field H_{ac} using a logarithmic scale. The external stress is there the parameter. Up to a certain critical field the susceptibility χ is nearly constant, then it deviates. This critical field is called pinning field H_p. The vertical thick curve gives the stress dependence of the pinning field. Above H_p the signal also becomes frequency dependent as shown in Fig. 2 on the sample $Co_{73.5}Cu_1Nb_3Si_{13.5}B_9$ indicating time-dependent effects above H_p which were also observed recently.[5] The existence of a nonlinear response for fields larger than H_p was demonstrated analyzing the frequency spectrum of the signal in a similar experiment performed on a zero-

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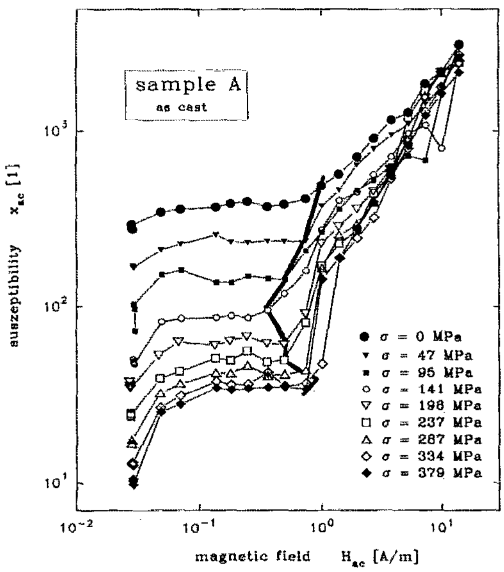

FIG. 1. Field dependence of the susceptibility as measured on as-cast sample A (E4229-VAC) at room temperature. The external stress is the parameter. The thick curve shows the stress dependence of the pinning field.

magnetostrictive ribbon of composition $Co_{70.4}Fe_{4.6}Si_{15}B_{10}$.[6] For $H_{ac} > H_p$ higher harmonics appear and their contribution increases with increasing H_{ac}.

Figure 3 shows as a comparison the stress dependence of the coercivity as measured on three different positions on the ribbon of sample A. Figure 4 shows the same for the pinning field. The shape of the $H_C(\sigma)$ as well as of the $H_p(\sigma)$ curves is always similar indicating that these curves are indeed representative for the ribbon. At higher external stresses the coercivity, but also the pinning field, depends on a premagnetizing procedure. The experimental process is as follows: A certain external stress is applied on the ribbon; also a certain dc field H_{pre} is applied parallel to the ribbon axis with the aid of Helmholtz coils—the magnitude of this field (where a new domain pattern is created) depends on the selected external stress as can be seen from Fig. 5 (minimum about 240 A/m); then this field is reduced to zero. The measurement of the hysteresis loop is

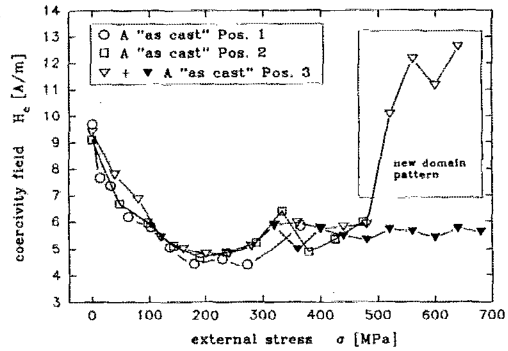

FIG. 3. Stress dependence of the coercivity field as measured on ribbon A (E4229-VAC) on position 1 (○), position 2 (□), and on position 3 (▽). The points marked with (▼) are measured after applying the premagnetizing procedure.

performed in a field range of ∓ 80 A/m (less than a quarter of H_{pre}). The thus created domain pattern can be destroyed applying a magnetic field H_{pre} with the opposite sign and following then the same measuring procedure as described above. Figure 5 shows the dependence of the thus determined H_C value as a function of this premagnetizing field. A systematic variation of H_C with the premagnetizing field but depending also on the external stress is obvious. The dependence of H_C and H_p on a premagnetizing procedure as well as the upturn that occurs for $H_C(\sigma)$ and $H_p(\sigma)$ for higher external stresses (see Figs. 3 and 4) can be explained assuming a history dependence of the pinning field. This means that, depending on the field treatment of the ribbon before each measurement, another domain pattern is formed.

In order to demonstrate this, in Fig. 6 two hysteresis loops applying a σ value of 700 MPa are shown. The right-hand-side hysteresis loop was obtained after the application of a premagnetizing procedure; the left-hand-side loop represents the original state. The latter loop shows a remarkable asymmetry. Asymmetric hysteresis loops were reported for heat-treated amorphous ribbons of composition $Co_{70.5}Fe_{4.5}Si_{10}B_{15}$ also applying a longitudinal field.[7]

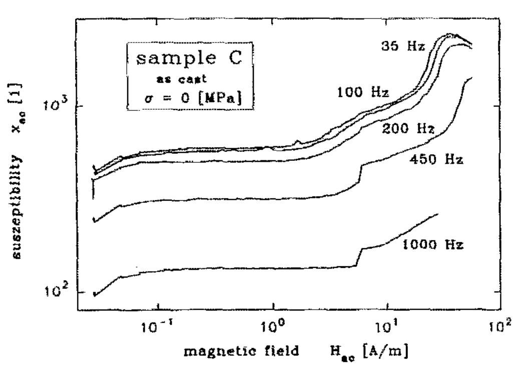

FIG. 2. Field dependence of the susceptibility as measured on as-cast $Co_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (sample C) at room temperature, applying no external stress. Here the measuring frequency is the parameter.

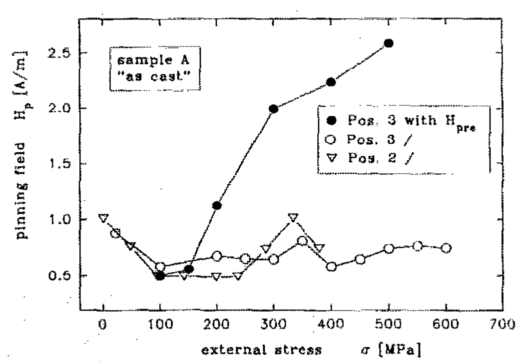

FIG. 4. Stress dependence of the pinning field as measured on ribbon A (E4229-VAC) on position 2 (▽), position 3 (○), and also on position 3 (●) but applying the corresponding premagnetizing field before the measurement.

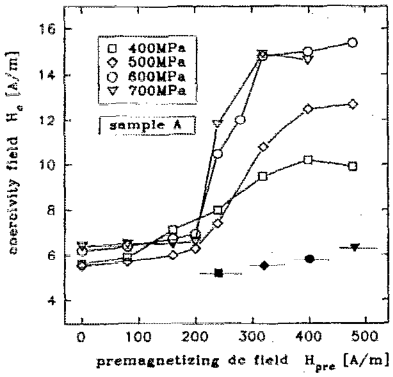

FIG. 5. Dependence of the coercivity field on a premagnetizing dc field as measured on ribbon A (E4229-VAC) under $\sigma_{ext}=400$ MPa (□), $\sigma_{ext}=500$ MPa (◇), $\sigma_{ext}=600$ MPa (○), and $\sigma_{ext}=700$ MPa (▽). The coercivity field as obtained in the original domain state is identical with that H_C value measured, after applying H_{pre} with the opposite sign—the corresponding points are ■, ◆, ●, ▼.

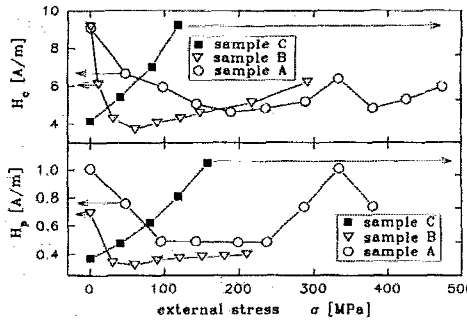

FIG. 7. Stress dependence of the coercivity H_C and the pinning field H_p as measured on ribbons A (E4229-VAC) (○), B (Torino) (▽), and C, composition $Co_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (■).

The asymmetric loop was explained as a surface effect; this is also believed to be the case here.

In a previous paper we discussed the effects of different quenching rates of these ribbons with a nanocrystalline composition.[8] Figure 7 compares as a summary the stress dependence of the coercivity H_C and the pinning field H_p as measured on samples A, B, and C. The different shape of the stress dependence of the coercivity can be taken as a clear indication of the quenched-in stresses. Additionally $H_p(\sigma)$ and $H_C(\sigma)$ show for sample A a minimum at $\sigma=200$ whereas for sample B the minimum is at 70 MPa. It can be assumed that at this minimum the external stress overweights the internal quenched-in stress. For the ribbon with the composition $Co_{73.5}Cu_1Nb_3Si_{13.5}B_9$ $H_C(\sigma)$ as well as $H_p(\sigma)$ increases with increasing external stress, as can be expected for a material with negative magnetostriction. Comparing now $H_C(\sigma)$ with the stress dependence of the pinning field it is worth noting that in all cases investigated here the stress dependence is similar. This indicates that the pinning field is the most important factor determining the coercivity. Regarding the field dependence of the susceptibility (see Figs. 1 and 2) it is obvious that always the lowest-lying field, indicating the deviation from a constant susceptibility, is called the pinning field. In reality a distribution of pinning fields have to be assumed according to a distribution of stress centers of different shape and size. The pinning field determined here is the smallest of these fields, the coercivity field is the highest-lying pinning field. A similar assumption can be used also to explain the temperature dependence of these pinning fields.[6]

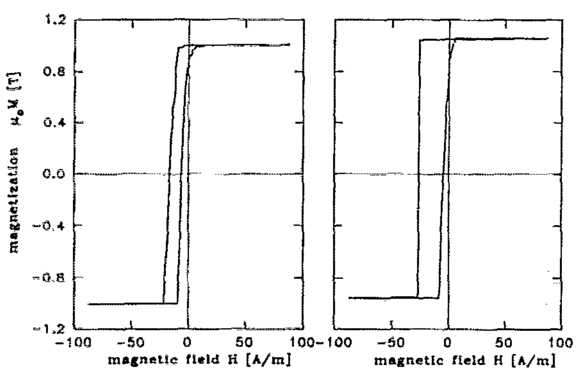

FIG. 6. Hysteresis loops as measured on ribbon A (E4229-VAC) under $\sigma_{ext}=700$ MPa. Left-hand-side loop: original domain state; right-hand-side loop: after applying the premagnetizing field.

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